



US009143219B1

(12) **United States Patent**
Palanivelu et al.

(10) **Patent No.:** **US 9,143,219 B1**
(45) **Date of Patent:** ***Sep. 22, 2015**

(54) **EQUAL POWER OUTPUT SPATIAL SPREADING MATRIX FOR USE IN A WIRELESS MIMO COMMUNICATION SYSTEM**

(71) Applicant: **MARVELL INTERNATIONAL LTD.**,
Hamilton (BM)

(72) Inventors: **Arul Durai Murugan Palanivelu**,
Sunnyvale, CA (US); **Hui-Ling Lou**,
Sunnyvale, CA (US); **Kedar Shirali**,
Sunnyvale, CA (US); **Rohit U. Nabar**,
Sunnyvale, CA (US); **Atul Salhotra**,
Santa Clara, CA (US)

(73) Assignee: **Marvell International Ltd.**, Hamilton
(BM)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 0 days.

This patent is subject to a terminal dis-
claimer.

(21) Appl. No.: **14/320,098**

(22) Filed: **Jun. 30, 2014**

Related U.S. Application Data

(63) Continuation of application No. 13/932,862, filed on
Jul. 1, 2013, now Pat. No. 8,767,863, which is a
continuation of application No. 13/567,763, filed on
Aug. 6, 2012, now Pat. No. 8,477,869, which is a

(Continued)

(51) **Int. Cl.**
H04B 7/06 (2006.01)

(52) **U.S. Cl.**
CPC **H04B 7/0678** (2013.01)

(58) **Field of Classification Search**

CPC H04B 7/024; H04B 7/0404; H04B 7/0408;
H04B 7/0413; H04B 7/0678; H04L 25/03891;
H04L 25/0391
USPC 375/141, 146, 259, 260, 262, 265, 267;
370/208, 210, 335, 342; 455/24, 500,
455/68, 69, 88, 553.1, 101, 103
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,760,388 B2 7/2004 Ketchum et al.
7,065,146 B1 6/2006 Lou et al.

(Continued)

OTHER PUBLICATIONS

International Standard, ISO/IEC 8802-11, ANSI/IEEE Std 802.11,
“Information technology—Telecommunications and information
exchange between systems—local and metropolitan area networks—
specific requirements” Part 11: Wireless LAN Medium Access Con-
trol (MAC) and Physical Layer (PHY) specifications, *The Institute of
Electrical and Electronics Engineers, Inc.*, pp. 1-512 (1999).

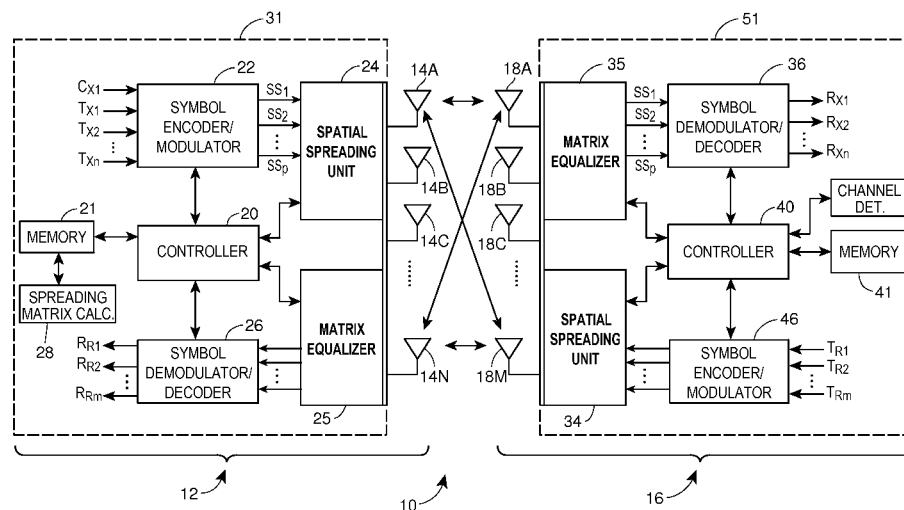
(Continued)

Primary Examiner — Young T Tse

(57) **ABSTRACT**

A transceiver utilizes a spatial spreading matrix to distribute
two or more encoded spatial data streams to multiple anten-
nas. The spatial spreading matrix satisfies one or more of the
following two constraints: (a) the ratio of squared norms of
the sum of the components of a row, for different rows of the
spatial spreading matrix, is equal to a first constant sequence,
and (b) the ratio of squared norms of the sum of a symbol S_1
to be transmitted, when the symbol S_1 is equal to 1 or -1,
multiplied by each of the components of a row, for different
rows of the spatial spreading matrix, is equal to a second
constant sequence.

28 Claims, 5 Drawing Sheets



Related U.S. Application Data

continuation of application No. 12/788,081, filed on May 26, 2010, now Pat. No. 8,238,466, which is a continuation of application No. 11/851,237, filed on Sep. 6, 2007, now Pat. No. 7,751,495.

- (60) Provisional application No. 60/824,701, filed on Sep. 6, 2006.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,302,238	B2	11/2007	Fujii	
7,346,115	B2 *	3/2008	Howard et al.	375/260
7,386,076	B2	6/2008	Onggosanusi et al.	
7,570,696	B2	8/2009	Maltsev et al.	
7,751,495	B1	7/2010	Palanivelu et al.	
7,787,554	B1	8/2010	Nabar et al.	
8,238,466	B2	8/2012	Palanivelu et al.	
8,477,869	B1	7/2013	Palanivelu et al.	
8,767,863	B1	7/2014	Palanivelu et al.	
2002/0196842	A1	12/2002	Onggosanusi et al.	
2003/0157954	A1 *	8/2003	Medvedev et al.	455/522
2005/0052991	A1 *	3/2005	Kadous	370/216
2005/0281350	A1	12/2005	Chae et al.	
2006/0209814	A1	9/2006	Fujii	
2006/0274687	A1 *	12/2006	Kim	370/328
2006/0274844	A1 *	12/2006	Walton et al.	375/260
2007/0041457	A1 *	2/2007	Kadous et al.	375/260
2007/0165738	A1 *	7/2007	Barriac et al.	375/267
2007/0211814	A1	9/2007	Walton et al.	
2008/0232503	A1	9/2008	Kim	
2008/0260002	A1	10/2008	Zhang et al.	
2008/0266176	A1	10/2008	Nabar et al.	
2009/0080566	A1	3/2009	Tong et al.	

OTHER PUBLICATIONS

IEEE Std 802.11a-1999 (Supplement to IEEE Std 802.11-1999)
 “Supplement to IEEE Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements—Part

11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-Speed Physical Layer in the 5 GHz Band,” *The Institute of Electrical and Electronics Engineers, Inc.*, pp. 1-83 (1999).

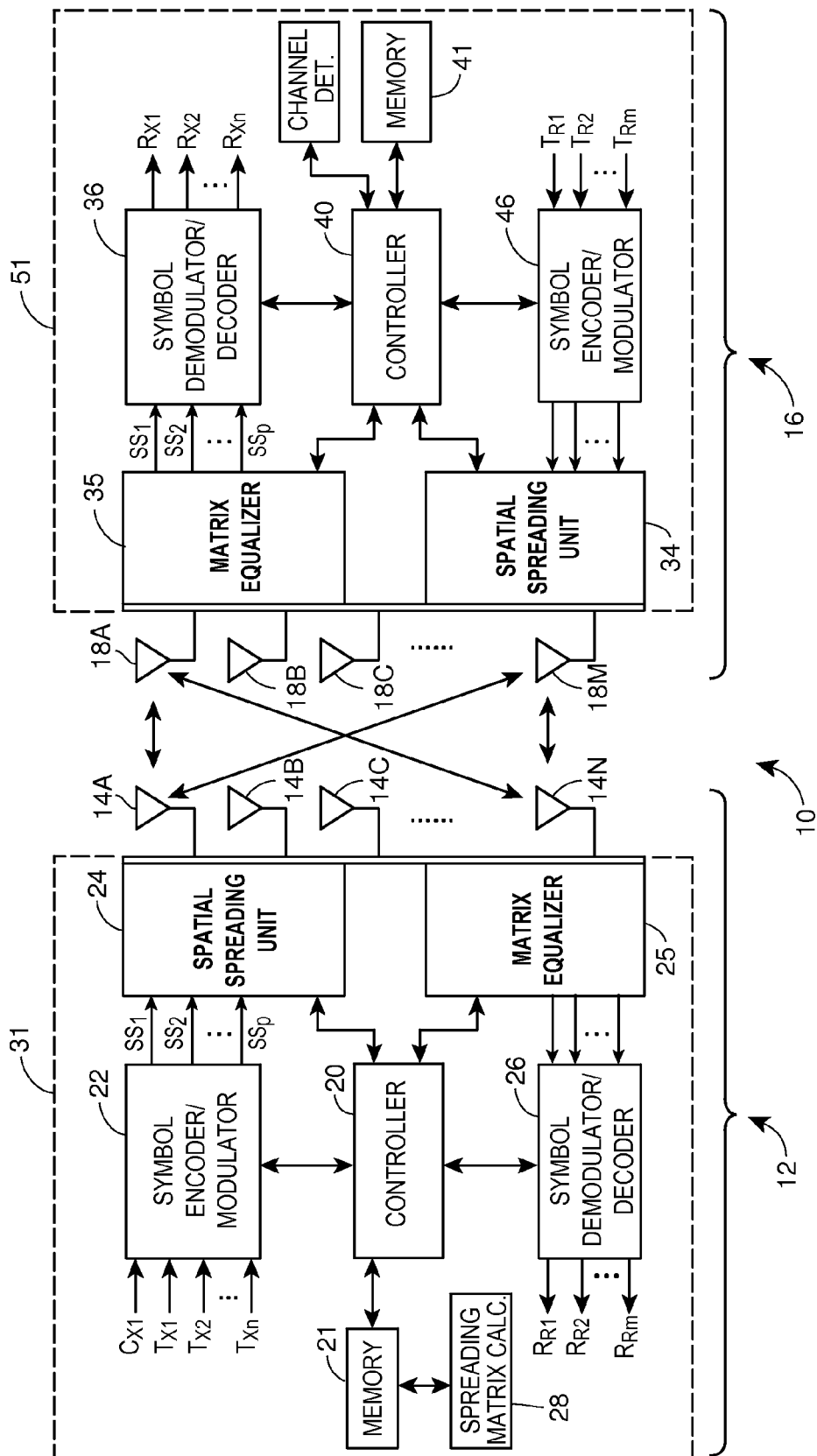
IEEE Std 802.11b-1999 (Supplement to ANSI/IEEE Std 802.11, 1999 Edition) “Supplement to IEEE Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher-speed Physical Layer Extension in the 2.4 GHz Band,” *The Institute of Electrical and Electronics Engineers, Inc.*, pp. 1-89 (1999).

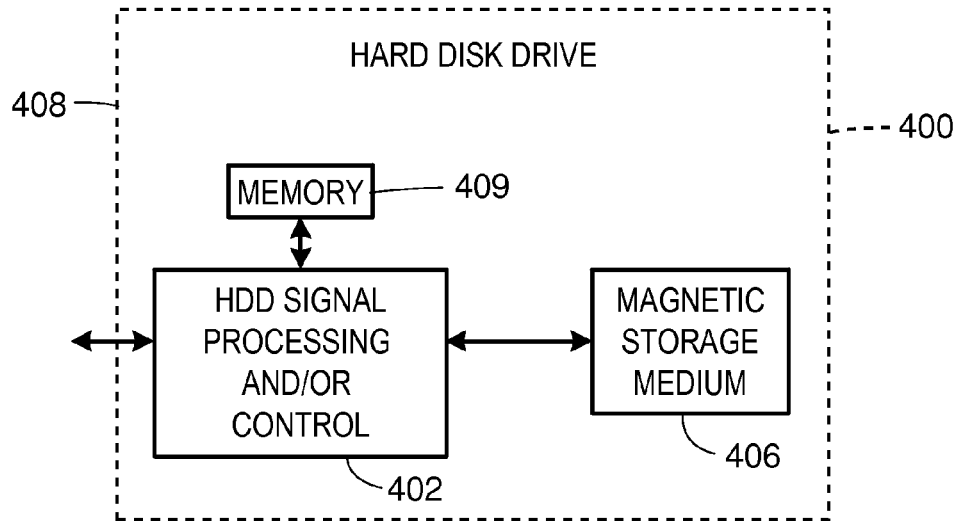
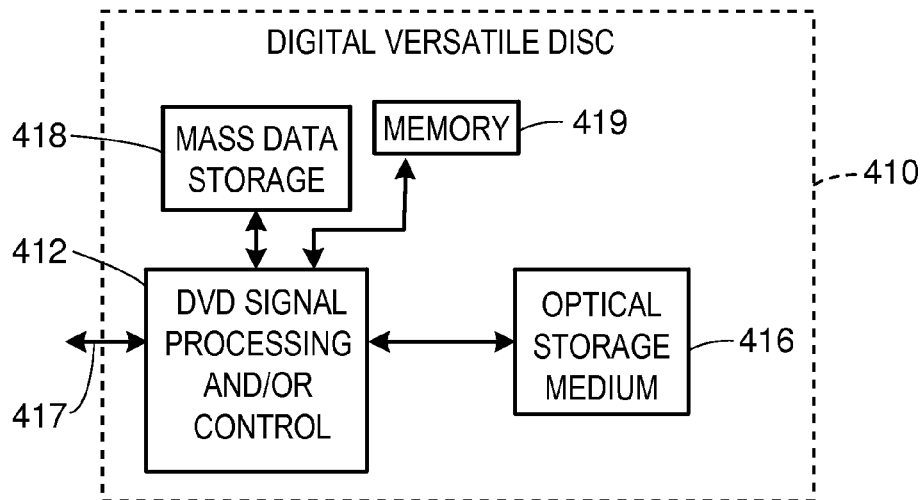
IEEE Std 802.11g/D2.8, May 2002 (Supplement to ANSI/IEEE Std 802.11, 1999 Edition) “Draft Supplement to Standard [for] Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Further Higher-Speed Physical Layer Extension in the 2.4 GHz Band,” *The Institute of Electrical and Electronics Engineers, Inc.*, pp. 1-53 (May 2002).
 IEEE Std 802.11g/D8.2, Apr. 2003 (Supplement to ANSI/IEEE Std 802.11, 1999 (Reaff 2003)) “Draft Supplement to Standard [for] Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Further Higher Data Rate Extension in the 2.4 GHz Band,” *The Institute of Electrical and Electronics Engineers, Inc.*, pp. 1-69 (Apr. 2003).

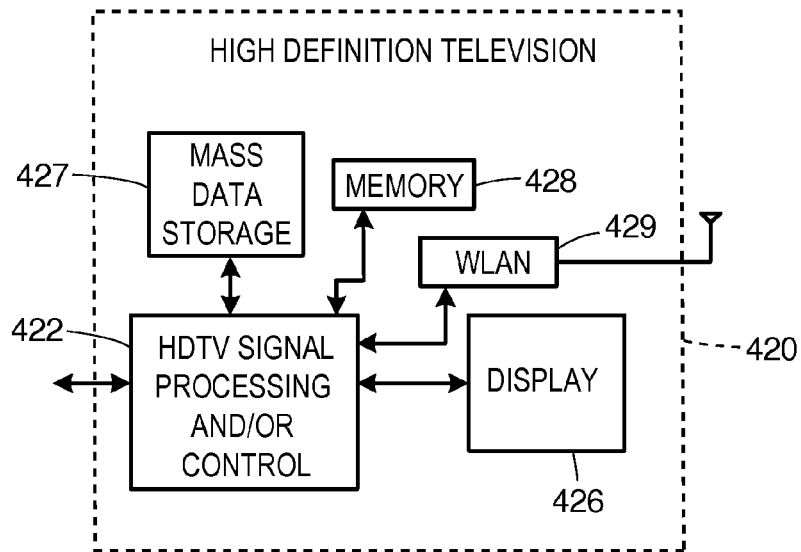
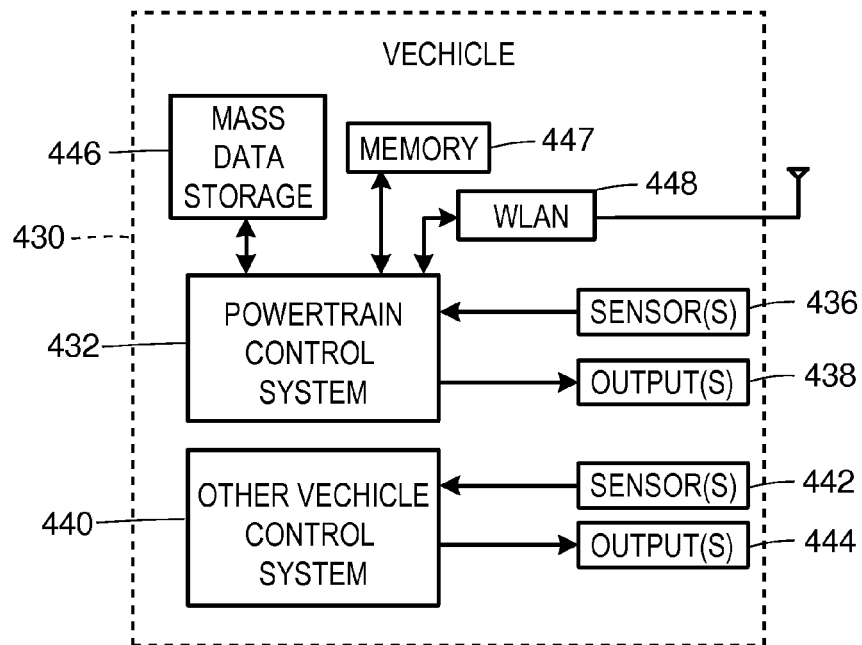
IEEE Std 802.16a-2003 (Amendment to IEEE Std 802.16-2001) “IEEE Standard for Local and metropolitan area networks: Part 16: Air Interface for Fixed Broadband Wireless Access Systems—Amendment 2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11 GHz,” *The Institute of Electrical and Electronics Engineers, Inc.*, pp. 1-292 (Apr. 1, 2003).
 Mujtaba, S.A. “IEEE P802.11—Wireless LANs, TGN Sync Proposal Technical Specification,” *The Institute of Electrical and Electronics Engineers, Inc.*, doc.: IEEE 802.11-04/0889r6, pp. 1-131 (May 2005).

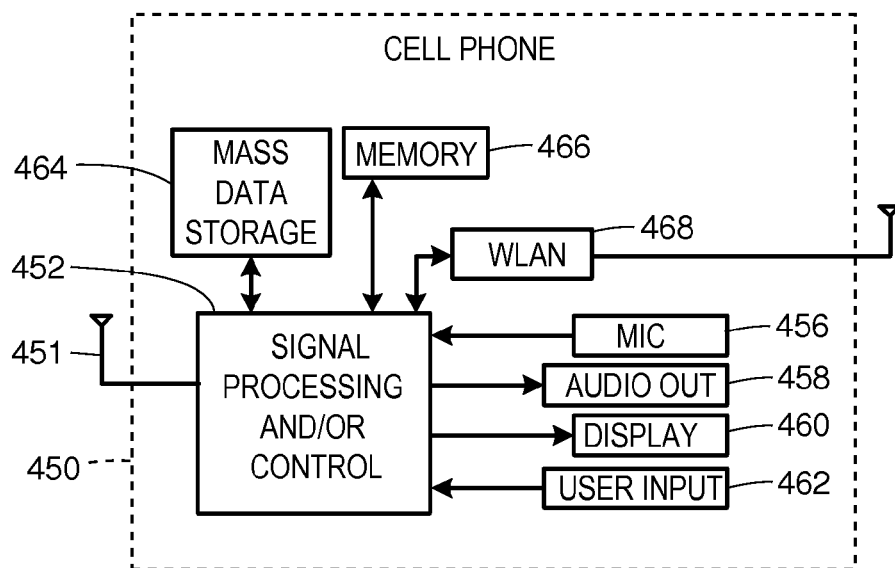
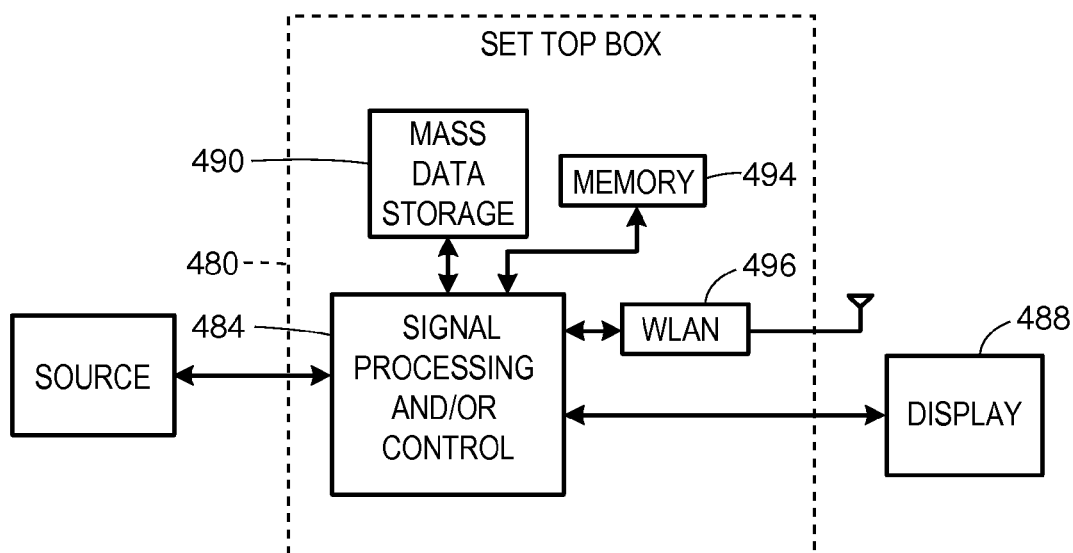
* cited by examiner

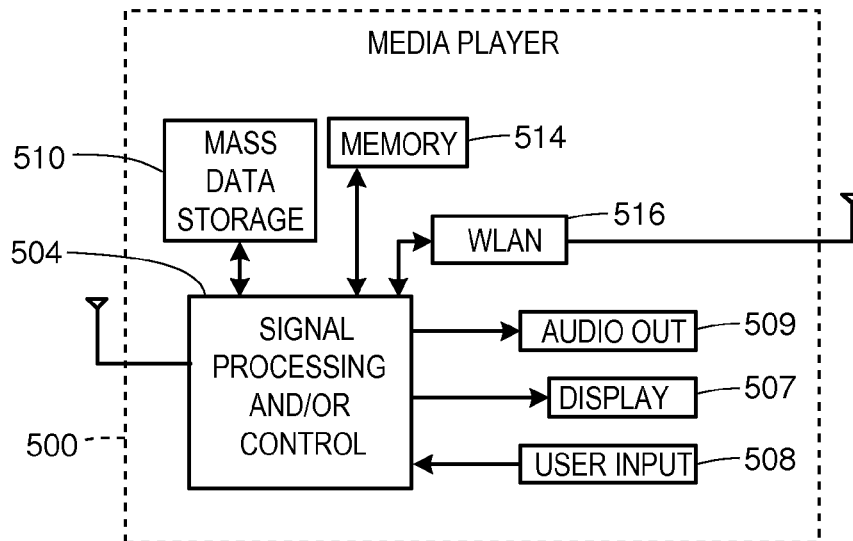
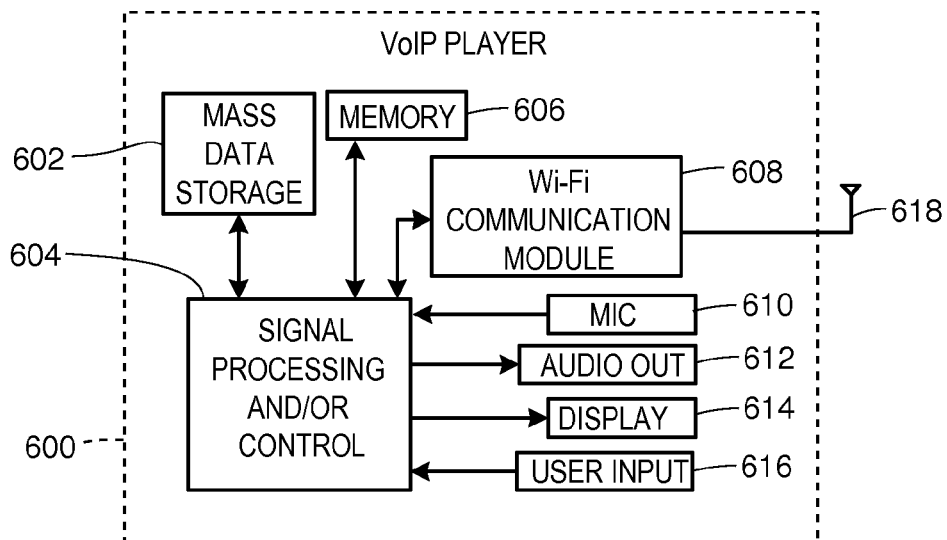
FIG. 1



**FIG. 2A****FIG. 2B**

**FIG. 2C****FIG. 2D**

**FIG. 2E****FIG. 2F**

**FIG. 2G****FIG. 2H**

1

EQUAL POWER OUTPUT SPATIAL SPREADING MATRIX FOR USE IN A WIRELESS MIMO COMMUNICATION SYSTEM

CROSS-REFERENCES TO RELATED APPLICATIONS

The present application is a continuation of U.S. patent application Ser. No. 13/932,862, entitled "Equal Power Output Spatial Spreading Matrix for Use in a Wireless MIMO Communication System," filed on Jul. 1, 2013, now U.S. Pat. No. 8,767,863, which is a continuation of U.S. patent application Ser. No. 13/567,763, entitled "Equal Power Output Spatial Spreading Matrix for use in a Wireless MIMO Communication System," filed on Aug. 6, 2012, now U.S. Pat. No. 8,477,869, which is a continuation of U.S. patent application Ser. No. 12/788,081, entitled "Equal Power Output Spatial Spreading Matrix for Use In a Wireless MIMO Communication System," filed on May 26, 2010, now U.S. Pat. No. 8,238,466, which is a continuation of U.S. patent application Ser. No. 11/851,237, entitled "Equal Power Output Spatial Spreading Matrix for Use In a Wireless MIMO Communication System," filed on Sep. 6, 2007, now U.S. Pat. No. 7,751,495, which claims priority to U.S. Provisional Application No. 60/824,701, entitled "Spatial Spreading Matrix Design For Equal Power Output on All Transmit Antennas," filed on Sep. 6, 2006. All of the applications referenced above are hereby incorporated by reference herein in their entireties.

FIELD OF TECHNOLOGY

The present disclosure relates generally to wireless communication systems and, more particularly, to a system and method for the simultaneous transmission of multiple streams of information or data in a multiple-input, multiple-output wireless communication system.

BACKGROUND

An ever-increasing number of relatively cheap, low power wireless data communication services, networks and devices have been made available over the past number of years, promising near wire speed transmission and reliability. Various wireless technologies are described in detail in the 802.11 IEEE Standard, including for example, the IEEE Standard 802.11a (1999) and its updates and amendments, the IEEE Standard 802.11g (2003), as well as the IEEE Standard 802.11n now in the process of being adopted, all of which are collectively incorporated herein fully by reference. These standards have been or are in the process of being commercialized with the promise of 54 Mbps or more effective throughput, making them a strong competitor to traditional wired Ethernet and the more ubiquitous "802.11b" or "WiFi" 11 Mbps mobile wireless transmission standard.

Generally speaking, transmission systems compliant with the IEEE 802.11a and 802.11g or "802.11a/g" as well as the 802.11n standards achieve their high data transmission rates using Orthogonal Frequency Division Modulation or OFDM encoded symbols mapped up to a 64 quadrature amplitude modulation (QAM) multi-carrier constellation. In a general sense, the use of OFDM divides the overall system bandwidth into a number of frequency sub-bands or channels, with each frequency sub-band being associated with a respective sub-carrier upon which data may be modulated. Thus, each frequency sub-band of the OFDM system may be viewed as an independent transmission channel within which to send data,

2

thereby increasing the overall throughput or transmission rate of the communication system.

Transmitters used in the wireless communication systems that are compliant with the aforementioned 802.11a/802.11g/ 802.11n standards as well as other standards such as the 802.16a IEEE Standard, typically perform multi-carrier OFDM symbol encoding (which may include error correction encoding and interleaving), convert the encoded symbols into the time domain using Inverse Fast Fourier Transform (IFFT) techniques, and perform digital to analog conversion and conventional radio frequency (RF) upconversion on the signals. These transmitters then transmit the modulated and upconverted signals after appropriate power amplification to one or more receivers, resulting in a relatively high-speed time domain signal with a large peak-to-average ratio (PAR).

Likewise, the receivers used in the wireless communication systems that are compliant with the aforementioned 802.11a/802.11g/802.11n and 802.16a IEEE standards typically include an RF receiving unit that performs RF down-conversion and filtering of the received signals (which may be performed in one or more stages), and a baseband processor unit that processes the OFDM encoded symbols bearing the data of interest. The digital form of each OFDM symbol presented in the frequency domain is recovered after baseband downconverting, conventional analog to digital conversion and Fast Fourier Transformation of the received time domain signal. Thereafter, the baseband processor performs demodulation and frequency domain equalization (FEQ) to recover the transmitted symbols, and these symbols are then processed with an appropriate FEC decoder, e.g. a Viterbi decoder, to estimate or determine the most likely identity of the transmitted symbol. The recovered and recognized stream of symbols is then decoded, which may include deinterleaving and error correction using any of a number of known error correction techniques, to produce a set of recovered signals corresponding to the original signals transmitted by the transmitter.

In wireless communication systems, the RF modulated signals generated by the transmitter may reach a particular receiver via a number of different propagation paths, the characteristics of which typically change over time due to the phenomena of multi-path and fading. Moreover, the characteristics of a propagation channel differ or vary based on the frequency of propagation. To compensate for the time varying, frequency selective nature of the propagation effects, and generally to enhance effective encoding and modulation in a wireless communication system, each receiver of the wireless communication system may periodically develop or collect channel state information (CSI) for each of the frequency channels, such as the channels associated with each of the OFDM sub-bands discussed above. Generally speaking, CSI is information describing one or more characteristics of each of the OFDM channels (for example, the gain, the phase and the SNR of each channel). Upon determining the CSI for one or more channels, the receiver may send this CSI back to the transmitter, which may use the CSI for each channel to pre-condition the signals transmitted using that channel so as to compensate for the varying propagation effects of each of the channels.

To further increase the number of signals which may be propagated in the communication system and/or to compensate for deleterious effects associated with the various propagation paths, and to thereby improve transmission performance, it is known to use multiple transmission and receive antennas within a wireless transmission system. Such a system is commonly referred to as a multiple-input, multiple-output (MIMO) wireless transmission system and is specific-

cally provided for within the 802.11n IEEE Standard now being adopted. As is known, the use of MIMO technology produces significant increases in spectral efficiency, throughput and link reliability, and these benefits generally increase as the number of transmission and receive antennas within the MIMO system increases.

In particular, in addition to the frequency channels created by the use of OFDM, a MIMO channel formed by the various transmission and receive antennas between a particular transmitter and a particular receiver includes a number of independent spatial channels. As is known, a wireless MIMO communication system can provide improved performance (e.g., increased transmission capacity) by utilizing the additional dimensionalities created by these spatial channels for the transmission of additional data. Of course, the spatial channels of a wideband MIMO system may experience different channel conditions (e.g., different fading and multi-path effects) across the overall system bandwidth and may therefore achieve different SNRs at different frequencies (i.e., at the different OFDM frequency sub-bands) of the overall system bandwidth. Consequently, the number of information bits per modulation symbol (i.e., the data rate) that may be transmitted using the different frequency sub-bands of each spatial channel for a particular level of performance may differ from frequency sub-band to frequency sub-band.

It is known that the use of multiple spatial channels in a MIMO system significantly increases throughput of the system as multiple streams of data can be sent through the system simultaneously. Thus, the use of multiple antennas within the MIMO system allows the use of multiple spatial streams, each of which includes streams of encoded data that are independently modulated and transmitted from the antennas. Generally speaking, the number of spatial streams is less than or is equal to the number of transmit antennas. When the number of transmit antennas is equal to the number of spatial streams, the modulated symbols of the spatial stream are spread evenly across the transmission antennas (i.e., one spatial stream per antenna) and are transmitted in parallel from the transmission antennas. However, when the number of spatial streams is less than number of transmission antennas, a spatial spreading matrix is used to map the spatial streams onto the transmission antennas to provide for maximum usage of the transmission antennas and thus maximum throughput. Generally speaking, it is possible to use a different spatial spreading matrix for each of the separate or possible tones or combinations of tones of the modulation system (wherein each tone relates to a different one of the possible symbols) to thereby allocate or to provide a spatial spreading matrix for use with the system that is optimally configured to send each of the separate tones. However, this system requires storing of a significant number of different spatial spreading matrices based on the tones, the number of tones and the combinations of tones sent in the system, and thus requires a significant amount of memory to store the spatial spreading matrixes. This requirement is especially true in the larger systems that have a significant number of spatial streams and/or transmission antennas. Generally speaking, in these systems as well as in other systems, the spatial spreading matrix is chosen to have orthogonal columns, so as to allocate the same amount of energy in each spatial stream.

However, from an implementation perspective, it is easier to design a transmission system having a single spatial spreading matrix that is used for all of the possible tones or combinations of tones. In the past, it was known and generally accepted to use a discrete Fourier transform (DFT) unity

antennas. Moreover, it has been typical to use only a portion of the DFT unity matrix (determined for the number of transmission antennas being used) when the number of spatial streams is less than the number of transmission antennas. Thus, in a system in which two spatial streams are transmitted simultaneously through three transmission antennas, two columns of the three-by-three DFT unitary matrix might be used as the spatial spreading matrix.

While such a system is generally acceptable when the data being sent within the separate signal streams is uncorrelated, and thus is random with respect to one another, problems can arise when the data being sent between the separate signal streams is correlated, which frequently occurs in communication systems that have predefined headers such as in communication systems using the 802.11(x) standards. In this case, significant portions of the symbol bit streams within the two separate spatial streams are correlated with one another, and can result in one of the transmission antennas transmitting a significantly higher power than the other transmission antennas. Thus, for example, when three transmission antennas are used to transmit two separate bit or symbol streams, and the two separate bit or symbol streams have the identical data, the first transmission antenna might end up being used to transmit at, for example, four times the power as the other two transmission antennas.

This unequal power situation causes a problem because the power amplifiers used in transmission systems generally have non-linear characteristics when operated well outside of a normal operating range. Thus, if two transmission antennas transmit at a particular power which is within the normal operating range of the associated power amplifiers, and one of the transmission antennas transmits at four times that power, this last transmission antenna may operate in a non-linear or abnormal region of the power amplifier, causing the power amplifier of this last transmission antenna to fail to properly amplify the signal as compared to the amplification provided by the other two transmission paths. These non-linearities result, on the receiver side of the transmission system, in distortions within the data, which leads to possible improper decoding of symbols at the receiver side, resulting in high and possibly unacceptable data error rates.

SUMMARY OF THE DISCLOSURE

In one embodiment, an apparatus comprises a transceiver configured to: produce two or more encoded spatial data streams, wherein a number of the encoded spatial data streams is different than a number of antennas to be used to transmit the encoded spatial data streams, and utilize a spatial spreading matrix to distribute the two or more encoded spatial data streams to the antennas. Additionally, the transceiver includes a memory to store the spatial spreading matrix. The spatial spreading matrix has components (i) associated with each row of a row dimension having a number of rows equal to the number of the antennas to be used to transmit the encoded spatial data streams and (ii) associated with each column of a column dimension having a number of columns equal to the number of the encoded spatial data streams to be transmitted. Also, the spatial spreading matrix satisfies one or more of the following two constraints: (a) the ratio of squared norms of the sum of the components of a row, for different rows of the spatial spreading matrix, is equal to a first constant sequence, and (b) the ratio of squared norms of the sum of a symbol S1 to be transmitted, when the symbol S1 is equal to 1 or -1, multiplied by each of the components of a row, for different rows of the spatial spreading matrix, is equal to a second constant sequence.

In another embodiment, an apparatus comprises a transceiver configured to: produce two or more encoded spatial data streams for transmission via a plurality of antennas, and utilize a spatial spreading matrix to distribute the two or more encoded spatial data streams to the antennas. Also, the transceiver includes a memory to store the spatial spreading matrix. The spatial spreading matrix has components (i) associated with each row of a row dimension having a number of rows equal to the number of the transmission antennas to be used to transmit the two or more encoded spatial data streams and (ii) associated with each column of a column dimension having a number of columns equal to a number of the encoded spatial data streams to be transmitted. Additionally, the sum of squared norms of the components of a row is equal to the squared norm of the sum of the components of the row for each row of the spatial spreading matrix.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a wireless MIMO communication system that determines and uses a spatial spreading matrix to provide for equal power output at all of the transmission antennas of a transmitter; and

FIGS. 2A-2H illustrate examples of various different devices in which a wireless communication system implementing the transmission techniques described herein may be used.

DETAILED DESCRIPTION

While the transmission techniques described herein for processing and effecting a wireless data transmission are described as being used in communication systems that use one of the IEEE Standard 802.11(x) communication standards, these techniques may be used in various other types of wireless communication systems and are not limited to those conforming to one or more of the IEEE Standard 802.11(x) standards.

Referring now to FIG. 1, a MIMO communication system 10 is illustrated in block diagram form as generally including a single transmitter 12 having multiple transmission antennas 14A-14N and a single receiver 16 having multiple receiver antennas 18A-18M. The number of transmission antennas 14A-14N can be the same as, more than, or less than the number of receiver antennas 18A-18M. As shown in FIG. 1, the transmitter 12 may include a controller 20 coupled to a memory 21, to a symbol encoder and modulator unit 22 and to a spatial spreading block 24. The transmitter 12 may also include a matrix equalizer 25 and a symbol demodulator and decoder unit 26 to perform demodulation and decoding of signals received via the antennas 14A-14N in a receive mode. Additionally, in some instances, the transmitter 12 may include a spreading matrix calculation unit 28.

The controller 12 may be any desired type of controller and the controller 12 and the spreading matrix calculation unit 28 may be implemented as one or more standard multi-purpose, programmable processors, such as micro-processors, as application specific integrated circuits (ASICs), etc., or may be implemented using any other desired types of hardware, software and/or firmware. Likewise, the spatial spreading block 24, and the matrix equalizer 25 may be implemented using known or standard hardware and/or software elements. If desired, various of the transmitter components, such as the controller 20, the modulator unit 22, the demodulator unit 26, the spreading matrix calculation unit 28, the spatial spreading block 24 and the matrix equalizer 25 may be implemented in the same or in different hardware devices, such as in the same

or different processors. Additionally, each of these components of the transmitter 12 may be disposed in a housing 31 (shown in dotted relief in FIG. 1) and the routines or instructions for implementing the functionality of any of these components may be stored in the memory 21 or within other memory devices associated with the individual hardware used to implement these components.

Likewise, if desired, one or more pre-calculated or predetermined spreading matrices may be stored in the memory 21 and used in the spreading matrix block 24 at various times or under various different conditions. Thus, for example, a different pre-calculated or predetermined spatial spreading matrix may be stored for each of a number of possible combinations of encoded spatial streams of data to be transmitted and transmission antennas 14 to be used to simultaneously transmit these encoded spatial streams of data. Thus, for example, a different spatial spreading matrix may be calculated and stored for two spatial streams of data being sent via three of the transmission antennas 14, for two spatial streams of data being sent via four of the transmission antennas 14, for three spatial streams of data being sent via five transmission antennas 14, etc. In this manner, the communication system 10 may optimally send different numbers of spatial streams of data at different times, depending on the load of the system. Moreover, the communication system 10 may also use these various different pre-stored or pre-calculated spatial spreading matrices to account for or to adapt to the loss of one or more of the transmission antennas 14 to be used in sending data within the communication system 10.

During operation, information signals T_{x1} - T_{xm} which are to be transmitted from the transmitter 12 to the receiver 16 are provided to the symbol encoder and modulator unit 22 for encoding and modulation. Of course, any desired number of signals T_{x1} - T_{xm} may be provided to the modulator unit 22, with this number generally being limited by the modulation scheme used by and the bandwidth associated with the MIMO communication system 10. Additionally, the signals T_{x1} - T_{xm} may be any type of signals, including analog or digital signals, and may represent any desired type of data or information. Additionally, if desired, a known test or control signal C_{x1} (which may be stored in the memory 21) may be provided to the symbol encoder and modulator unit 22 for use in determining CSI related information describing the characteristics of the channel(s) between the transmitter 12 and the receiver 16. If desired, the same control signal or a different control signal may be used to determine the CSI for each frequency and/or spatial channel used in the MIMO communication system 10.

The symbol encoder and modulator unit 22 may interleave digital representations of the various signals T_{x1} - T_{xm} and C_{x1} and may perform any other known type(s) of error-correction encoding on the signals T_{x1} - T_{xm} and C_{x1} to produce one or more encoded streams of symbols SS_1, SS_2, \dots, SS_p to be modulated and sent from the transmitter 12 to the receiver 16. While the symbol streams SS_1 - SS_p may be modulated using any desired or suitable QAM technique, such as using 64 QAM, these symbols may be modulated in any other known or desired manner including, for example, using any other desired phase and/or frequency modulation techniques. In any event, the modulated encoded symbol streams SS_1 - SS_p are provided by the symbol encoder and modulator unit 22 to the spatial spreading block 24 for processing before being transmitted via the antennas 14A-14N. While not specifically shown in FIG. 1, the modulated symbol streams SS_1 - SS_p may be processed by the spatial spreading block 24 that implements a spatial spreading matrix in accordance with a transmission technique more specifically described below, before

being up-converted to the RF carrier frequencies associated with an OFDM technique (in one or more stages). Upon receiving the modulated signals, the spatial spreading block 24 processes the modulated signals by injecting delays and/or gains into the modulated signals based on a spatial spreading matrix which may be provided by, for example, the controller 12, to thereby perform mixing and transmission of the spatial streams of data across the transmission antennas 14A-14N.

The signals transmitted by the transmitter 12 are detected by the receiver antennas 18A-18M and may be processed by a matrix equalizer 35 within the receiver 16 to enhance the reception capabilities of the antennas 18A-18M. As will be understood, the processing applied at the receiver 16 (as well as at the transmitter 12) may be based on, for example, the CSI developed by the receiver 16 in response to the transmission of the test or control signal C_{x1} . In particular, a controller 40 or other unit within the receiver 16, such as a channel determination unit 39, may process the received control signal C_{x1} and develop therefrom a measured description of the forward channel between the transmitter 12 and the receiver 16 by determining or characterizing the propagation effects of the forward channel on the signal C_{x1} as it traveled through the forward channel. In any event, a symbol demodulator and decoder unit 36, under control of the controller 40, may decode and demodulate the received symbol strings SS_1 - SS_p as recovered by the matrix equalizer 35. In this process, these signals may be downconverted to baseband. Generally, the demodulator and decoder unit 36 may operate to remove effects of the forward channel based on the CSI as well as to perform demodulation on the received symbols in each symbol stream SS_1 - SS_p to produce a digital bit stream for each stream. In some cases, if desired, the symbol demodulator and decoder unit 36 may perform error correction decoding and deinterleaving on the bit stream to produce the received signals R_{x1} - R_{xm} corresponding to the originally transmitted signals T_{x1} - T_{xm} .

As shown in FIG. 1, the receiver 16 may also include a memory 41 and a symbol encoder and modulator unit 46 which may receive one or more signals T_{R1} - T_{Rm} encoded and modulated using any desired encoding and modulation techniques. The receiver 16 may also provide one or more known test or control signals C_{R1} to the symbol encoder/modulator unit 46 to be sent to the transmitter 12 to enable the transmitter 12 to determine a measured description of the reverse channel between the receiver 16 and the transmitter 12. The encoded and modulated symbol stream may then be upconverted and processed by a spatial spreading block 34 which may use a spatial spreading matrix developed according to the principles described herein based on the number of symbol streams to be sent simultaneously and the number of transmission antennas 18 to be used. The output of the spatial spreading block 34 is then transmitted via the receiver antennas 18A-18N to, for example, the transmitter 12, thereby implementing the reverse link. As shown in FIG. 1, each of the receiver components may be disposed in a housing 51.

The matrix equalizer 25 and the demodulator/decoder unit 26 within the transmitter 12 operate similarly to the matrix equalizer 35 and the demodulator/decoder unit 36 of the receiver 16 to demodulate and decode the symbol streams transmitted by the receiver 16 to produce the recovered signals R_{R1} - R_{Rm} . Here again, the matrix equalizer 25 may process the received signals in any known manner to enhance the separation and therefore the reception of the various symbol streams transmitted by the antennas 18A-18M. Of course, the CSI or other measured description of the forward channel for the various OFDM channel(s) may be used to process or decode the received signals.

As indicated above, it is desirable to use a spatial spreading matrix which produces a power output proportional to the linear operating regions of the power amplifiers for each of the transmission antennas under all conditions, including when the data within the separate symbol streams SS_1 - SS_p is either correlated or uncorrelated. Typically, any matrix with orthogonal columns is used as a spreading matrix, because such a matrix allocates the same energy to each stream. Generally speaking, much of the information or data within the data packets of the streams of data being sent using, for example the 802.11n standard, is uncorrelated, as the data in one symbol stream it is not related to data in other symbols streams, in which case these spatial spreading matrices work as intended. However, there are certain portions of the data packets used in the 802.11n standard which may contain highly correlated data across spatial streams, including packet header information within the data packets of the various different symbol streams. For example, the HT-SIG and the HT-LTF portion of the data packets of the 802.11n standard results in spatial streams that are not uncorrelated on a per-OFDM symbol basis. In fact, during the HT-SIG section, all spatial streams are identical while, during a particular HT-LTF section, any two spatial symbols are either identical or are negatives of one another. These situations result in highly correlated data within the various spatial data streams being transmitted which can result, using many prior art transmission techniques, in a condition in which one of the transmission antennas used to transmit the separate data streams operates at a significantly different power output level than other ones of the antennas, thereby potentially leading to transmission and decoding problems.

A spatial spreading matrix that provides for power output that is proportional to the operating regions of the corresponding power amplifiers across all of the transmission antennas of a transmission system when transmitting correlated and uncorrelated data within two or more spatial streams of data being sent simultaneously via two or more transmission antennas may be determined as a spatial spreading matrix that satisfies five separate constraints, as explained in more detail below. In particular, when the spatial spreading matrix is not a square matrix because the number of transmission antennas is greater than the number of spatial streams, the spatial spreading matrix will still produce equal power output across the antennas in all cases when it is configured or determined so as to satisfy a combination of and, preferably, all five of separate constraints discussed below. Thus, any spatial spreading matrix which satisfies all of these constraints (or in some cases some combination of a sub-set of these constraints) can be used in the spatial spreading block 24 of FIG. 1 to deliver equal or appropriately proportional power output across the separate transmission antennas 14 in all conditions, that is when the data or symbols being sent are either correlated or uncorrelated.

In particular, the goal is to design a spatial spreading matrix Q which is the same for all tones k so that the spatial spreading matrix for each tone $Q_k = Q$. The five constraints which are defined below generally in an equation format may be used to design or calculate a spatial spreading matrix which reaches this goal. In particular, when the data streams are uncorrelated, the transmit power of the i^{th} antenna during the data segment of a packet is proportional to the square of the i^{th} row norm of the spatial spreading matrix Q because the data streams are independent. If the power amplifiers for all of the transmitters have similar performance behavior, the spatial spreading matrix Q should have equal row norms for all of the number of transmitter N_{TX} rows of the matrix Q . Otherwise, the output power of some transmission antennas may be

significantly higher than the others, leading to high distortion due to inherent non-linear input-output characteristics of typical power amplifiers. This requirement leads to the first three constraints defined below.

The first constraint, as defined in equation (1) below, basically requires that the sum of the squared norms of the column components of a column of the spatial spreading matrix be the same for all of the spatial streams, i.e., for each column of the spatial spreading matrix. This constraint may be defined mathematically as:

$$\sum_{t=1}^{N_{TX}} |Q(t, l)|^2 = C, \text{ for each and every spatial stream } l = 1 \dots N_{SS} \quad (1)$$

wherein:

N_{TX} =number of transmitters;

N_{SS} =number of spatial streams;

C =a constant; and

$Q(t, l)$ =the spatial spreading matrix component at row t , column l .

The second constraint, as defined in equation (2) below, requires that the inner product of any two different columns of the spatial spreading matrix be equal to zero for every set of two different columns (i.e., for every set of two columns which are not the same column). Generally speaking, this constraint means that the columns of the spatial spreading matrix define orthogonal vectors with respect to each other, thereby leading to a zero cross product between any two different columns. This constraint can be defined mathematically as:

$$\sum_{t=1}^{N_{TX}} Q(t, l)Q^*(t, m) = 0, \text{ for all } l \neq m \quad (2)$$

wherein:

N_{TX} =number of transmitters;

$Q(t, l)$ =the spatial spreading matrix component at row t , column l ;

and

$Q^*(t, m)$ =the component of the transpose of the spatial spreading matrix at row t , column m .

The third constraint, as defined in equation (3) below, requires that the sum of the squared norms of the row components of a row of the spatial spreading matrix is equal to a constant, and is the same for each of the rows of the spatial spreading matrix, when all the transmit antennas have power amplifiers with similar operating behavior. The constant, defined in equation (3) below as " A ," need not be zero but can instead be non-zero, although this constant should be the same for every row. This third constraint can be defined mathematically as:

$$\sum_{l=1}^{N_{SS}} |Q(t, l)|^2 = A, \text{ and is same for all } t = 1 \dots N_{TX}. \quad (3)$$

wherein:

N_{SS} =number of spatial streams;

N_{TX} =number of transmitters;

$Q(t, l)$ =the spatial spreading matrix component at row t , column l ;

and

A =a constant.

If the transmit antennas have power amplifiers that have different linear operating regions, then the ratio of sum of the squared norms of the row components of a row, for different rows of the spatial spreading matrix, is the same as a constant sequence designed based on the linear operating regions of the power amplifiers, denoted here by $A_1, A_2, \dots, A_{N_{TX}}$. This constraint is defined mathematically as:

$$\sum_{l=1}^{N_{SS}} |Q(t, l)|^2 = A_t B, \text{ for all } t = 1 \dots N_{TX}. \quad (3a)$$

wherein:

N_{SS} =number of spatial streams;

N_{TX} =number of transmitters;

$Q(t, l)$ =the spatial spreading matrix component at row t , column l ;

and

B =a constant.

Generally speaking, in the past, non-square spatial spreading matrices which were based on a unitary matrix (e.g., which were simply portions of a DFT matrix), satisfied these three constraints. Furthermore, a spatial spreading matrix that satisfies these three constraints works adequately to transmit different symbol streams when the data in the symbol streams is uncorrelated.

However, the following two constraints are useful when spatial streams having correlated data are sent simultaneously via the same transmission system, which is frequently the case with, for example, the HT-SIG and HT-LTF portions of data packets sent using the 802.11n standard. The fourth constraint as defined in equation (4) below requires that the squared norm of the sum of the row components of a row of the spatial spreading matrix is equal to a constant for each row of the spatial spreading matrix, and in particular, is equal to the same constant as the sum of the squared norms of the row components defined by equation (3), when all the transmit antennas have power amplifiers with similar operating behavior. This fourth constraint is related to the third constraint in that it requires that, for a particular row, the sum of the squared norms for that row is equal to the squared norm of the sum of the components of that row. The fourth constraint can be defined mathematically as:

$$\left| \sum_{l=1}^{N_{SS}} Q(t, l) \right|^2 = A, \text{ and is same for all } t = 1 \dots N_{TX}. \quad (4)$$

wherein:

N_{SS} =number of spatial streams;

$Q(t, l)$ =the spatial spreading matrix component at row t , column l ;

and

A =a constant.

If the transmit antennas have power amplifiers that have different linear operating regions, then the ratio of squared norm of the sum of the row components of a row, for different rows of the spatial spreading matrix, is the same as the constant sequence designed based on the linear operating regions of the power amplifiers: $\{A_1, A_2, \dots, A_{N_{TX}}\}$. This constraint is defined mathematically as:

11

$$\left| \sum_{l=1}^{N_{SS}} Q(t, l) \right|^2 = A_t B \text{ for all } t = 1 \dots N_{TX}. \quad (4a)$$

wherein:

N_{SS} =number of spatial streams;

N_{TX} =number of transmitters;

$Q(t, l)$ =the spatial spreading matrix component at row t , column l ;

and

B =a constant.

The fifth constraint requires that the power within a particular row when the symbol being transmitted is a 1 or a -1 should also be equal to the constant A defined within the third and fourth constraints provided above. Thus, the squared norm of the sum of the symbol S_t (when the symbol S_t is equal to 1 or -1) multiplied by each of the row components of a row should also be equal to the constant A for each row of the spatial spreading matrix, when all the transmit antennas have power amplifiers with similar operating behavior. The fifth constraint can be defined mathematically as:

$$\left| \sum_{l=1}^{N_{SS}} S_t Q(t, l) \right|^2 = A \quad (5)$$

wherein:

N_{SS} =number of spatial streams;

$Q(t, l)$ =the spatial spreading matrix component at row t , column l ;

A =a constant; and

1 or -1 depending on the HT-LTF.

If the transmit antennas have power amplifiers that have different linear operating regions, then the ratio of squared norm of the sum of the symbol S_t (when the symbol S_t is equal to 1 or -1) multiplied by each of the row components of a row, for different rows of the spatial spreading matrix, is the same as the constant sequence designed based on the linear operating regions of the power amplifiers: $\{A_1, A_2, \dots, A_{N_{TX}}\}$. This constraint is defined mathematically as:

$$\left| \sum_{l=1}^{N_{SS}} S_t Q(t, l) \right|^2 = A_t B \text{ for all } t = 1 \dots N_{TX}. \quad (5a)$$

wherein:

N_{SS} =number of spatial streams;

N_{TX} =number of transmitters;

$Q(t, l)$ =the spatial spreading matrix component at row t , column l ;

and

B =a constant.

Any spatial spreading matrix which satisfies these five constraints (or in some cases, some combination of a subset of these constraints) can be used in any square transmission system (having the same number of spatial streams and transmission antennas) or in any non-square transmission system (having multiple symbol streams of data transmitted via a different number of transmission antennas) to assure equal power output for each of the transmission antennas, averaged over each symbol period. However, the use of a spatial spreading matrix that satisfies these constraints is generally

12

more relevant or useful in cases in which a strict unity DFT matrix cannot be used because of the non-square nature of the transmission system. In particular, a spatial spreading matrix as defined above can be used advantageously in non-square systems and is especially advantageous when the number of transmission antennas is greater than the number of symbol streams and in which the number of symbol streams is greater than or equal to two. Some example spatial spreading matrices which satisfy the five constraints defined above are provided below for a 3x2 system (three transmission antennas used to simultaneously send two spatial streams), a 4x2 system (four transmission antennas used to simultaneously transmit two spatial streams), and a 4x3 system (four transmission antennas used to simultaneously transmit three spatial streams), all with the power amplifiers for different transmit antennas having identical or similar operating behavior.

$$3 \times 2: \begin{bmatrix} \sqrt{\frac{1}{3}} & j\sqrt{\frac{1}{3}} \\ \sqrt{\frac{2}{3}} \cos(15^\circ) & -j\sqrt{\frac{2}{3}} \sin(15^\circ) \\ \sqrt{\frac{2}{3}} \sin(15^\circ) & -j\sqrt{\frac{2}{3}} \cos(15^\circ) \end{bmatrix}$$

$$4 \times 2: \begin{bmatrix} 1/2 & j/2 \\ 1/2 & j/2 \\ 1/2 & -j/2 \\ 1/2 & -j/2 \end{bmatrix}$$

$$4 \times 3: \begin{bmatrix} 1/\sqrt{2} & j/2 & 0 \\ 0 & 1/2 & j/\sqrt{2} \\ 1/\sqrt{2} & -j/2 & 0 \\ 0 & -1/2 & j/\sqrt{2} \end{bmatrix}$$

An example of spatial spreading matrix design based of the above constraints for a 3x2 system, with the power amplifier for the first transmit antenna having a linear operating region that is roughly two times the operating region of the other transmit antennas, is shown below:

$$3 \times 2: \begin{bmatrix} \sqrt{\frac{1}{2}} & j\sqrt{\frac{1}{2}} \\ \frac{1}{2} & -j\frac{1}{2} \\ \frac{1}{2} & -j\frac{1}{2} \end{bmatrix}$$

However, it is noted that these spatial spreading matrices are not unique for these types of systems, and in fact other and different spatial spreading matrices can be determined for 3x2 systems, 4x2 systems and 4x3 systems which satisfy the five constraints defined herein. Still further, if desired, other spatial spreading matrices may be determined and used for other system sizes or configurations, such as 5x2, 5x3, 5x4, 6x2, 6x3, 6x4, etc. systems. As will be understood, the man-

13

ner in which the spatial spreading matrices are calculated or determined is not particularly important, as long as the resulting spatial spreading matrices satisfy one or more, and preferably all of the five constraints defined above. Thus, any mathematical, heuristic, iterative, or trial and error method can be used to actually determine or compute any particular size of spatial spreading matrix that satisfies the constraints defined herein, and the method used to compute a spatial spreading matrix that satisfies these constraints (or some combination of these constraints) is not determinative. Moreover, the specific orientation or definition of the “row” and “column” dimensions of a matrix as used herein is arbitrary and is simply based on convention, and therefore may be changed. Thus, for example, the row dimension can be a horizontal dimension with the column dimension being a vertical dimension (as assumed herein), or the row dimension can be a vertical dimension with the column dimension being a horizontal dimension.

If desired, a spatial spreading matrix determined according to the principles defined above may be pre-calculated and stored in the memory 21 of the transmitter 12 and may be used within the spatial spreading block 24 when needed. Still further, as noted above, a number of different spatial spreading matrices may be stored in the memory 21 of the transmitter 12 to be used in different situations, such as when different numbers of encoded spatial streams of data are to be transmitted simultaneously or when different numbers of the transmission antennas 14 are available. Thus, it may be possible to detect the failure of one or more of the antennas 14 and still operate using multiple spatial streams by switching to the use of a new spatial spreading matrix configured to transmit the same number of spatial streams using a fewer number of antennas. Likewise, it may be possible to switch the number of spatial streams being sent via the same number of transmission antennas 14 or to switch both the number of spatial streams being sent and the number of transmission antennas 14 used by simply obtaining from the memory 21 a new spatial spreading matrix designed for the particular combination of the number of spatial streams to be sent and the number of available antennas. In other words, the transmission system may switch between different modes, wherein each mode as a unique combination of number of spatial streams and number of antennas, and a separate or different spatial spreading matrix may be pre-calculated and stored to be used in the spatial spreading block 24 for each of these different modes. However, instead of or in addition to storing pre-determined spatial spreading matrices, one or more spatial spreading matrices may be calculated during operation of the system by, for example, the spatial spreading matrix calculation unit 28.

Moreover, it will be understood that the actual spatial spreading matrix equations, e.g., the computation of a particular spatial spreading matrix that satisfies the constraints defined above, may be performed at any desired location within the wireless communication system 10 of FIG. 1, including within the controller 20 or other hardware, software, or firmware of the transmitter 12, as well as within the controller 40 or other hardware, software, or firmware of the receiver 16. Alternatively, the spatial spreading matrix may be pre-computed and stored in the memory 21 (or 41) or other memory of the system 10 prior to the transmission system being used. The spatial spreading matrix or matrices may also be computed or determined by a different device and may be sent to the transmitter 12 or the receiver 14 of the transmission system 10 at any desired time.

Of course, the spatial spreading matrix technique described herein is not limited to being used in a transmitter of

14

a MIMO communication system communicating with a single receiver of the MIMO communication system, but can additionally be applied when a transmitter of a MIMO communication system is communicating with multiple receivers, each of which has one or more receiver antennas associated therewith.

While the spatial spreading matrix calculations described herein are described in one example as being implemented in software stored in, for example, one of the memories 21, 41 and implemented on a processor associated with one of the controllers 20, 40, or with the spatial spreading matrix calculation unit 28 of the MIMO communication system 10 of FIG. 1, these routines may alternatively or additionally be implemented in digital or analog hardware, firmware, application specific integrated circuits, etc., as desired. If implemented in software, the routines may be stored in any computer readable memory such as in RAM, ROM, flash memory, a magnetic disk, a laser disk, or other storage medium. Likewise, this software may be delivered to a MIMO system device (such as a transmitter or a receiver) via any known or desired delivery method including, for example, over a communication channel such as a telephone line, the Internet, a wireless connection, etc., or via a transportable medium, such as a computer-readable disk, flash drive, etc.

The present invention may be embodied in any type of wireless communication system including, for example, ones used in wireless computer systems such as those implemented via a local area network or a wide area network, internet, cable and satellite based communication systems (such as internet, data, video and voice communication systems), wireless telephone systems (including cellular phone systems, voice over internet protocol (VoIP) systems, home-based wireless telephone systems, etc.) Referring now to FIGS. 2A-2H, various exemplary implementations of the present invention are shown.

Referring to FIG. 2A, the present invention may be used with a hard disk drive 400 which includes both signal processing and/or control circuits, which are generally identified in FIG. 2A at 402. In some implementations, signal processing and/or control circuit 402 and/or other circuits (not shown) in HDD 400 may process data, perform coding and/or encryption, perform calculations, and/or format data that is output to and/or received from a magnetic storage medium 406.

HDD 400 may communicate with a host device (not shown) such as a computer, mobile computing devices such as personal digital assistants, cellular phones, media or MP3 players and the like, and/or other devices via one or more wired or wireless communication links 408 which may implement the beamforming techniques described above. HDD 400 may be connected to memory 409, such as a random access memory (RAM), a low latency nonvolatile memory such as flash memory, read only memory (ROM) and/or other suitable electronic data storage.

Referring now to FIG. 2B, the present invention may be embodied in or used with a digital versatile disc (DVD) drive 410 which may include either or both signal processing and/or control circuits, which are generally identified in FIG. 2B at 412, and/or mass data storage 418 of DVD drive 410. Signal processing and/or control circuit 412 and/or other circuits (not shown) in DVD 410 may process data, perform coding and/or encryption, perform calculations, and/or format data that is read from and/or data written to an optical storage medium 416. In some implementations, signal processing and/or control circuit 412 and/or other circuits (not shown) in DVD 410 can also perform other functions such as

15

encoding and/or decoding and/or any other signal processing functions associated with a DVD drive.

DVD drive **410** may communicate with an output device (not shown) such as a computer, television or other device via one or more wired or wireless communication links **417** which may be implemented using the beamforming techniques described above. DVD **410** may communicate with mass data storage **418** that stores data in a nonvolatile manner. Mass data storage **418** may include a hard disk drive (HDD) such as that shown in FIG. 2A. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". DVD **410** may be connected to memory **419**, such as RAM, ROM, low latency nonvolatile memory such as flash memory, and/or other suitable electronic data storage.

Referring now to FIG. 2C, the present invention may be embodied in a high definition television (HDTV) **420** which may include either or both signal processing and/or control circuits, which are generally identified in FIG. 2C at **422**, a WLAN interface and/or mass data storage of the HDTV **420**. HDTV **420** receives HDTV input signals in either a wired or wireless format and generates HDTV output signals for a display **426**. In some implementations, signal processing circuit and/or control circuit **422** and/or other circuits (not shown) of HDTV **420** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other type of HDTV processing that may be required.

HDTV **420** may communicate with mass data storage **427** that stores data in a nonvolatile manner such as optical and/or magnetic storage devices. At least one HDD may have the configuration shown in FIG. 2A and/or at least one DVD may have the configuration shown in FIG. 2B. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". HDTV **420** may be connected to memory **428** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. HDTV **420** also may support connections with a WLAN via a WLAN network interface **429** which may implement the beamforming techniques described above.

Referring now to FIG. 2D, the present invention may be used in conjunction with a control system of a vehicle **430** having a WLAN interface and/or mass data storage. In some implementations, the present invention may be used within a powertrain control system **432** that receives inputs from one or more sensors such as temperature sensors, pressure sensors, rotational sensors, airflow sensors and/or any other suitable sensors and/or that generates one or more output control signals such as engine operating parameters, transmission operating parameters, and/or other control signals.

The present invention may also be embodied in other control systems **440** of vehicle **430**. Control system **440** may likewise receive signals from input sensors **442** and/or output control signals to one or more output devices **444**. In some implementations, control system **440** may be part of an anti-lock braking system (ABS), a navigation system, a telematics system, a vehicle telematics system, a lane departure system, an adaptive cruise control system, a vehicle entertainment system such as a stereo, DVD, compact disc and the like. Still other implementations are contemplated.

Powertrain control system **432** may communicate with mass data storage **446** that stores data in a nonvolatile manner. Mass data storage **446** may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. 2A and/or at least one DVD may have the configura-

16

tion shown in FIG. 2B. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Powertrain control system **432** may be connected to memory **447** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Powertrain control system **432** also may support connections with a WLAN via a WLAN network interface **448** which may implement the beamforming techniques described above. The control system **440** may also include mass data storage, memory and/or a WLAN interface (all not shown).

Referring now to FIG. 2E, the present invention may be embodied in a cellular phone **450** that may include one or more cellular antennas **451**, either or both signal processing and/or control circuits, which are generally identified in FIG. 2E at **452**, a WLAN interface and/or mass data storage of the cellular phone **450**. In some implementations, cellular phone **450** includes a microphone **456**, an audio output **458** such as a speaker and/or audio output jack, a display **460** and/or an input device **462** such as a keypad, pointing device, voice actuation and/or other input device. Signal processing and/or control circuits **452** and/or other circuits (not shown) in cellular phone **450** may process data, perform coding and/or encryption, perform calculations, format data and/or perform other cellular phone functions.

Cellular phone **450** may communicate with mass data storage **464** that stores data in a nonvolatile manner such as optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. 2A and/or at least one DVD may have the configuration shown in FIG. 2B. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Cellular phone **450** may be connected to memory **466** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Cellular phone **450** also may support connections with a WLAN via a WLAN network interface **468**.

Referring now to FIG. 2F, the present invention may be embodied in a set top box **480** including either or both signal processing and/or control circuits, which are generally identified in FIG. 2F at **484**, a WLAN interface and/or mass data storage of the set top box **480**. Set top box **480** receives signals from a source such as a broadband source and outputs standard and/or high definition audio/video signals suitable for a display **488** such as a television and/or monitor and/or other video and/or audio output devices. Signal processing and/or control circuits **484** and/or other circuits (not shown) of the set top box **480** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other set top box function.

Set top box **480** may communicate with mass data storage **490** that stores data in a nonvolatile manner. Mass data storage **490** may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. 2A and/or at least one DVD may have the configuration shown in FIG. 2B. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Set top box **480** may be connected to memory **494** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Set top box **480** also may support connections with a WLAN via a WLAN network interface **496** which may implement the beamforming techniques described herein.

Referring now to FIG. 2G, the present invention may be embodied in a media player **500**. The present invention may

17

implement either or both signal processing and/or control circuits, which are generally identified in FIG. 2G at 504, a WLAN interface and/or mass data storage of the media player 500. In some implementations, media player 500 includes a display 507 and/or a user input 508 such as a keypad, touchpad and the like. In some implementations, media player 500 may employ a graphical user interface (GUI) that typically employs menus, drop down menus, icons and/or a point-and-click interface via display 507 and/or user input 508. Media player 500 further includes an audio output 509 such as a speaker and/or audio output jack. Signal processing and/or control circuits 504 and/or other circuits (not shown) of media player 500 may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other media player function.

Media player 500 may communicate with mass data storage 510 that stores data such as compressed audio and/or video content in a nonvolatile manner. In some implementations, the compressed audio files include files that are compliant with MP3 format or other suitable compressed audio and/or video formats. The mass data storage may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. 2A and/or at least one DVD may have the configuration shown in FIG. 2B. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". Media player 500 may be connected to memory 514 such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. Media player 500 also may support connections with a WLAN via a WLAN network interface 516 which may implement the beamforming techniques described herein. Still other implementations in addition to those described above are contemplated.

Referring to FIG. 2H, the present invention may be embodied in a Voice over Internet Protocol (VoIP) phone 600 that may include one or more antennas 618, either or both signal processing and/or control circuits, which are generally identified in FIG. 2H at 604, and a wireless interface and/or mass data storage of the VoIP phone 600. In some implementations, VoIP phone 600 includes, in part, a microphone 610, an audio output 612 such as a speaker and/or audio output jack, a display monitor 614, an input device 616 such as a keypad, pointing device, voice actuation and/or other input devices, and a Wireless Fidelity (Wi-Fi) communication module 608. Signal processing and/or control circuits 604 and/or other circuits (not shown) in VoIP phone 600 may process data, perform coding and/or encryption, perform calculations, format data and/or perform other VoIP phone functions.

VoIP phone 600 may communicate with mass data storage 602 that stores data in a nonvolatile manner such as optical and/or magnetic storage devices, for example hard disk drives HDD and/or DVDs. At least one HDD may have the configuration shown in FIG. 2A and/or at least one DVD may have the configuration shown in FIG. 2B. The HDD may be a mini HDD that includes one or more platters having a diameter that is smaller than approximately 1.8". VoIP phone 600 may be connected to memory 606, which may be a RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. VoIP phone 600 is configured to establish communications link with a VoIP network (not shown) via Wi-Fi communication module 608 which may implement the beamforming techniques described herein.

Moreover, while the present invention has been described with reference to specific examples, which are intended to be illustrative only and not to be limiting of the invention, it will

18

be apparent to those of ordinary skill in the art that changes, additions and/or deletions may be made to the disclosed embodiments without departing from the spirit and scope of the invention.

What is claimed is:

1. An apparatus, comprising:

a symbol encoder unit configured to produce two or more encoded spatial data streams including at least first and second encoded spatial data streams, wherein a number, N_{SS} , of the encoded spatial data streams is less than a number, N_{TX} , of antennas to be used to transmit the encoded spatial data streams; and

a spatial spreading unit configured to utilize a spatial spreading matrix Q to distribute the two or more encoded spatial data streams to the antennas,

wherein:

at least a first portion of the first encoded spatial data stream is correlated with a corresponding portion of the second encoded spatial data stream,

the spatial spreading matrix Q has N_{TX} rows and N_{SS} columns,

a ratio of squared norms of a sum of components of a row, for different rows of the spatial spreading matrix Q , is equal to a first constant sequence, and

a ratio of squared norms of a sum of a symbol S_1 to be transmitted, when the symbol S_1 is equal to 1 or -1, multiplied by each of the components of a row, for different rows of the spatial spreading matrix Q , is equal to a second constant sequence.

2. The apparatus of claim 1, wherein the first constant sequence is designed based on linear operating regions of power amplifiers corresponding to the N_{TX} antennas when at least some of the power amplifiers have different operating regions.

3. The apparatus of claim 1, wherein the second constant sequence is designed based on linear operating regions of power amplifiers corresponding to the N_{TX} antennas when at least some of the power amplifiers have different operating regions.

4. The apparatus of claim 1, wherein the first constant sequence is equal to the second constant sequence.

5. The apparatus of claim 4, wherein the first constant sequence and the second constant sequence are designed based on linear operating regions of power amplifiers corresponding to the N_{TX} antennas when at least some of the power amplifiers have different operating regions.

6. The apparatus of claim 1, wherein the symbol S_1 is based on a long training field for the two or more encoded spatial data streams.

7. The apparatus of claim 6, wherein the first portion of the first encoded spatial data stream includes the long training field for the first encoded spatial data stream.

8. The apparatus of claim 1, wherein the first portion of the first encoded spatial data stream includes a signal field for the first encoded spatial data stream.

9. The apparatus of claim 1, wherein the first portion of the first encoded spatial data stream includes packet header information for the first encoded spatial data stream.

10. The apparatus of claim 1, wherein the spatial spreading matrix Q satisfies one or more of the following three constraints:

(a) the sum of squared norms of the components of a column of the spatial spreading matrix Q is the same for each column of the spatial spreading matrix Q ,

19

(b) an inner product of any two different columns of the spatial spreading matrix Q is equal to zero for every set of two different columns of the spatial spreading matrix Q , and

(c) the ratio of squared norms of the sums of the components of a row for different rows of the spatial spreading matrix Q is equal to the second constant sequence.

11. The apparatus of claim 10, wherein the spatial spreading matrix Q satisfies two of the constraints (a), (b), and (c).

12. The apparatus of claim 10, wherein the spatial spreading matrix Q satisfies each of the constraints (a), (b), and (c).

13. A method of wirelessly transmitting data via a plurality of antennas, comprising:

encoding the data to produce two or more encoded spatial data streams for transmission, including at least first and second encoded spatial data streams, via the antennas, wherein a number, N_{SS} , of the encoded spatial data streams is less than a number, N_{TX} , of antennas to be used to transmit the encoded spatial data streams;

using a spatial spreading matrix Q to distribute the two or more encoded spatial data streams to the number of the antennas, wherein the spatial spreading matrix Q has components associated with each row of a row dimension having a number of rows equal to the number of the antennas to be used to transmit the encoded spatial data streams and a column dimension having a number of columns equal to the number of the encoded spatial data streams to be transmitted, and wherein

at least a first portion of the first encoded spatial data stream is correlated with a corresponding portion of the second encoded spatial data stream,

the number of the encoded spatial data streams is less than the number of the antennas,

the spatial spreading matrix Q has N_{TX} rows and N_{SS} columns,

a ratio of squared norms of a sum of components of a row, for different rows of the spatial spreading matrix Q , is equal to a first constant sequence, and

a ratio of squared norms of a sum of a symbol S_1 to be transmitted, when the symbol S_1 is equal to 1 or -1, multiplied by each of the components of a row, for different rows of the spatial spreading matrix Q , is equal to a second constant sequence; and

simultaneously transmitting the distributed encoded spatial data streams via the number of the antennas.

14. The method of claim 13, wherein the first constant sequence is designed based on linear operating regions of power amplifiers corresponding to the N_{TX} antennas when at least some of the power amplifiers have different operating regions.

15. The method of claim 13, wherein the second constant sequence is designed based on linear operating regions of power amplifiers corresponding to the N_{TX} antennas when at least some of the power amplifiers have different operating regions.

16. The method of claim 13, wherein the first constant sequence is equal to the second constant sequence.

17. The method of claim 16, wherein the first constant sequence and the second constant sequence are designed based on linear operating regions of power amplifiers corresponding to the N_{TX} antennas when at least some of the power amplifiers have different operating regions.

18. The method of claim 13, wherein the symbol S_1 is based on a long training field for the two or more encoded spatial data streams.

20

19. The method of claim 18, wherein the first portion of the first encoded spatial data stream includes the long training field for the first encoded spatial data stream.

20. The method of claim 13, wherein the first portion of the first encoded spatial data stream includes a signal field for the first encoded spatial data stream.

21. The method of claim 13, wherein the first portion of the first encoded spatial data stream includes packet header information for the first encoded spatial data stream.

22. The method of claim 13, wherein the spatial spreading matrix Q satisfies one or more of the following three constraints:

(a) the sum of squared norms of the components of a column of the spatial spreading matrix Q is the same for each column of the spatial spreading matrix Q ,

(b) an inner product of any two different columns of the spatial spreading matrix Q is equal to zero for every set of two different columns of the spatial spreading matrix Q , and

(c) the ratio of squared norms of the sums of the components of a row for different rows of the spatial spreading matrix Q is equal to the second constant sequence.

23. The method of claim 22, wherein the spatial spreading matrix Q satisfies two of the constraints (a), (b), and (c).

24. The method of claim 22, wherein the spatial spreading matrix Q satisfies each of the constraints (a), (b), and (c).

25. A tangible, non-transitory computer readable medium or media storing instructions that, when executed by one or more processors, cause the one or more processors to:

encode data to produce two or more encoded spatial data streams for transmission, including at least first and second encoded spatial data streams, via a plurality of antennas, wherein a number, N_{SS} , of the encoded spatial data streams is less than a number, N_{TX} , of antennas to be used to transmit the encoded spatial data streams; and

use a spatial spreading matrix Q to distribute the two or more encoded spatial data streams to the number of the antennas, wherein the spatial spreading matrix Q has components associated with each row of a row dimension having a number of rows equal to the number of the antennas to be used to transmit the encoded spatial data streams and a column dimension having a number of columns equal to the number of the encoded spatial data streams to be transmitted, and wherein

at least a first portion of the first encoded spatial data stream is correlated with a corresponding portion of the second encoded spatial data stream,

the number of the encoded spatial data streams is less than the number of the antennas,

the spatial spreading matrix Q has N_{TX} rows and N_{SS} columns,

a ratio of squared norms of a sum of components of a row, for different rows of the spatial spreading matrix Q , is equal to a first constant sequence, and

a ratio of squared norms of a sum of a symbol S_1 to be transmitted, when the symbol S_1 is equal to 1 or -1, multiplied by each of the components of a row, for different rows of the spatial spreading matrix Q , is equal to a second constant sequence.

26. The tangible, non-transitory computer readable medium or media of claim 25, wherein the spatial spreading matrix Q satisfies one or more of the following three constraints:

(a) the sum of squared norms of the components of a column of the spatial spreading matrix Q is the same for each column of the spatial spreading matrix Q ,

(b) an inner product of any two different columns of the spatial spreading matrix Q is equal to zero for every set of two different columns of the spatial spreading matrix Q , and

(c) the ratio of squared norms of the sums of the components of a row for different rows of the spatial spreading matrix Q is equal to the second constant sequence. 5

27. The tangible, non-transitory computer readable medium or media of claim **26**, wherein the spatial spreading matrix Q satisfies two of the constraints (a), (b), and (c). 10

28. The tangible, non-transitory computer readable medium or media of claim **26**, wherein the spatial spreading matrix Q satisfies each of the constraints (a), (b), and (c).

* * * * *